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Upper-left gaze bias reveals competing search strategies in a reverse Stroop task

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Abstract

Three experiments with a total of 87 human observers revealed an upper-left spatial bias in the initial movement of gaze during visual search. The bias was present whether or not the explicit control of gaze was required for the task. This bias may be part of a search strategy that competed with the fixed-gaze parallel search strategy hypothesized by Durgin [Durgin, F. H. (2003). Translation and competition among internal representations in a reverse Stroop effect. *Perception & Psychophysics, 65,* 367–378.] for this task. When the spatial probabilities of the search target were manipulated either in accord with or in opposition to the existing upper-left bias, two orthogonal factors of interference in the latency data were differentially affected. The two factors corresponded to two different forms of representation and search. Target probabilities consistent with the gaze bias encouraged opportunistic serial search (including gaze shifts), while symmetrically opposing target probabilities produced latency patterns more consistent with parallel search based on a sensory code.
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1. Introduction

Stroop effects (Stroop, 1935), in which task-irrelevant (but related) information interferes with responding to task relevant information, have been studied as a kind of window on control procedures in human cognition both as instances of automatic processing of the unwanted information (stimulus competition) and as response competition (Cohen, Dunbar, & McClelland, 1990; Dyer, 1973; Kornblum, Hasbroucq, & Osman, 1990; MacLeod, 1991). However, Stroop phenomena also bear on the nature of the internal codes used to structure the connection between perception and action (Durgin, 2003; Glaser & Glaser, 1989; Hommel, 2004; Sugg & McDonald, 1994; Treisman & Fearnley, 1969; Virzi & Egeth, 1985). When a visual search task is defined by asking whether a specific color is present on the screen, but the color to be found is identified to the searcher by the verbal component of a Stroop word (e.g., the word "blue" printed in red text), the irrelevant conflicting color information produces a large cost on response latency (Durgin, 2000, 2003). Durgin (2003) argued that the cost was primarily a recoding cost. Efficient search required recoding the verbally defined target into sensory codes that could support parallel visual search. Here we report evidence from gaze-tracking supporting this basic model, but also showing that a second task strategy may exist alongside the one previously postulated.

Patterns of gaze are a basic tool for studying information flow in many fields of cognitive processing (see Irwin, 2004 for a review). In this paper we report the discovery of an unconscious gaze behavior that may reflect

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an unconscious search strategy. The behavior pattern we discovered is a directional bias of initial eye-movements in a Stroop-defined search task (though this directional bias may be more general). The effects of this gaze bias in the present task are best understood in terms of strategic information flow in a translation model. That is, our task can be accomplished by first doing a (costly) translation of the verbal information into a sensory representation and then initiating a rapid parallel search (Strategy 1) or by immediately initiating a (relatively slow) serial search (Strategy 2). We first present a brief review of the Stroop and reverse Stroop tasks from the perspective of a translation framework.

The classic Stroop task involves naming the sensory color in which a word is printed. Stroop (1935) showed that when the words are conflicting color names, the rate at which sensory print colors can be named is slowed dramatically, whereas the rate at which the words can be read is almost completely unaffected by the color in which they are printed. This asymmetry is a central feature of Stroop interference. There are thought to be many components to the Stroop effect (e.g., De Houwer, 2003; Kornblum et al., 1990; Melara & Mounts, 1993). However, Durgin (2000) showed that the asymmetry of interference in responding to Stroop words could be reversed entirely by a change in task (see also, Glaser & Glaser, 1989; Hommel, 2004; Sugg & McDonald, 1994; Treisman & Fearnley, 1969; Virzi & Egeth, 1985). When a color word was presented in a conflicting color, subjects showed little interference (~15 ms) from the verbal information in pointing to a color patch presented on the screen that matched the color. However, the color of the text produced nearly 80 ms of interference when the task was to respond to the verbal information itself (by pointing to a color patch) and ignore the color.

Durgin (2003) identified two separate components of this interference effect, called *Set* and *Match*. Set, which has been studied in normal Stroop paradigms (Klein, 1964; Proctor, 1978), refers to the difference in interference between distracters that are from within the response set compared to those outside. That is, of eight colors available, four were selected at random as those that would be (verbally-specified) targets for pointing during the experiment. The remaining four were used as distracters (text colors) or response alternatives only. When participants were required to find a color patch corresponding to the verbal information in a Stroop word, it was found that the cost of having the text color be from the set of possible target colors was about 30 ms relative to trials in which the text color was from outside the set of response colors (Durgin, 2003). Orthogonal to this manipulation of Set, Durgin manipulated whether the to-be-ignored text color on a given trial was present (had a Match) or not among the six colors available as response locations. There was only a 15 ms cost for Match trials relative to trials in which the text color was not among the alternatives. The Match effect was reliably smaller than the Set effect, and Set and Match did not interact in the latency data.

Durgin (2003) argued that the reversed Stroop asymmetry was best explained not by the pointing response used, but by the visual search task required to complete it. As a test of the visual search hypothesis, the same experiment was repeated as a go/no-go task in which participants had simply to indicate if the color named by the target word was present among six alternatives on the screen, without pointing to it. The results were essentially identical to those of the pointing task: There was again a 30 ms effect of Set and a 15 ms effect of Match.

To better understand the source of Match effects, we decided in the present work to use gaze as a dependent measure. We expected that because of the tight linkage between attention and gaze (Deubel & Schneider, 1996; Kowler, Anderson, Dosher, & Blaser, 1995; Kustov & Robinson, 1996), requiring people to control their gaze might reveal stronger disruptive effects of Match. As we will report below, the empirical contribution of our first experiment was surprising in two respects. It identified an unexpected spatial bias in gaze while also eliminating any direct evidence of the effects of Match on response latency. (Insofar as Match stimuli caused gaze errors, the reduction of Match effects on latency may be an artifact of the removal of error trials from analysis. Match effects will be shown to play only a minor role in accounting for gaze errors, however.)

In the experiments presented below, we will report that the gaze bias, toward the upper left, was present whether observers were required to use their gaze to respond (Experiment 1) or used a mouse cursor to point to targets (Experiment 2). In our third experiment, we examined the effects of either rewarding or punishing these unconscious initial gaze biases by manipulating the probable location of the target item in accord with or in opposition to the gaze bias (Experiment 3). The results of this manipulation suggest that the upper-left gaze bias is part of an exploratory search strategy that is at least partly serial (Strategy 2) and that normally competes with an efficient (presumably parallel) search strategy for a sensory color (Strategy 1). These two strategies seem to favor different forms of cognitive representation and to have different decision rules. Importantly, they appear to differentially contribute to the effects of Set and Match on latency. That is, the elimination of the Match effect from the latency data in Experiment 1 may take place because making gaze the response interfered with Strategy 2. Because error trials are not included in the latency analysis, trials normally responsible for the Match effect may be buried among the rather large number of error trials. Analysis of gaze data from this experiment and from Experiment 2 shows that sensory matches did indeed draw attention (i.e., gaze) to some extent.

The findings we report here suggest that the upper-left gaze bias may be part of an unconscious search routine wherein the controlling information used for the task is evidence of a match between an untransformed (verbal) representation of the target and successive color patches

(Strategy 2). It is unclear whether a full translation of the color patches into verbal codes is necessary. It seems possible that sensory matches produce conflict either because they satisfy the criterion of match, but in the wrong codes (see Egeth, Blecker, & Kamlet, 1969) or simply because they draw attention to themselves. The alternative (and theoretically more important) strategy in this reverse Stroop task (as suggested by Durgin, 2003) is to recode the verbal target into a (sensory) representation useful for guiding a (parallel) search for a sensory color (Strategy 1). This is the strategy that produces Set effects because the representations of certain sensory colors are primed in advance by previous trials. Encouraging one strategy over the other can be accomplished by biasing the distribution of targets to make the upper-left gaze bias of Strategy 2 efficient or inefficient.

The main theoretical implications of this work are twofold. First, the experiments provide convergent evidence for the idea behind translation models (i.e., Strategy 1): Different kinds of internal representation are available for performing many cognitive tasks and the choice of representation matters a great deal for performance. As we will report here, Set effects are fairly robust across most variations in the task. These are precisely the kinds of effects most important to establishing the idea of translation models. Second, involuntary gaze routines are implicated that seem to reflect an unconscious cognitive strategy – perhaps associated with a greater diffusion of attention; these routines appear to reflect representation-specific choices. The nature of the strategy is neither evident from the gaze data alone, nor from the latency data alone, but only from the conjoint examination of both.

2. Experiment 1: Gaze as response

The purpose of this experiment was to test the effect of using the gaze system as a response system in the reverse Stroop paradigm developed by Durgin (2003, Experiment 1). The older paradigm involved having participants use a mouse to indicate the location of a color patch (located in a hexagonal array) that corresponds to the color named by a target word. The names of four (randomly selected) colors were used as target words in any given run of the experiment, but four additional colors were available as distracter colors, so that distracter color (the print color of the text in which the target word is written) could be in the set of target colors or not. In addition, independent of Set, the six color patches used for response were newly distributed on each trial and may have contained a sensory match to the distracter color used on a given trial or not. Durgin (2003) argued that effects of Set were due to priming of certain internal sensory color representations whereas Match effects were attentional (possibly caused by perceptual grouping). Because of connections between gaze and attention systems (Deubel & Schneider, 1996; Kowler et al., 1995; Kustov & Robinson, 1996; but see Stelmach, Campsall, & Herdman, 1997), we originally expected that the use of a gaze response might be more susceptible to interference from Match effects insofar as these reflected attentional capture. Most current evidence suggests that attention precedes saccades (e.g., Gersch, Kowler, & Dosher, 2004), even when the saccades are involuntary (Peterson, Kramer, & Irwin, 2004).

2.1. Methods

2.1.1. Participants

Thirty Swarthmore College undergraduates were paid for their participation. All had normal color vision and were unaware of the specific hypotheses being tested. One participant's data were excluded from analysis because of extremely long latencies.

2.1.2. Displays and apparatus

An Eyelink® eye tracker (250 Hz) was used in association with a Macintosh G3 and a 17″ cathode ray tube display. Details concerning the coding of saccades are provided in the Appendix. Displays were viewed from a distance of approximately 45 cm, without restraint.

On each trial of the experiment, after fixation was established, a hexagonal array of six colored circles was presented simultaneously with a color word indicating the target color, as illustrated in Fig. 1. The circles in the array were 7° in diameter and centered 8° from fixation. The text was lowercase Times bold, approximately 1.5° high and up to 6° wide. The array remained present until gaze entered one of the colored circles, at which point that circle was

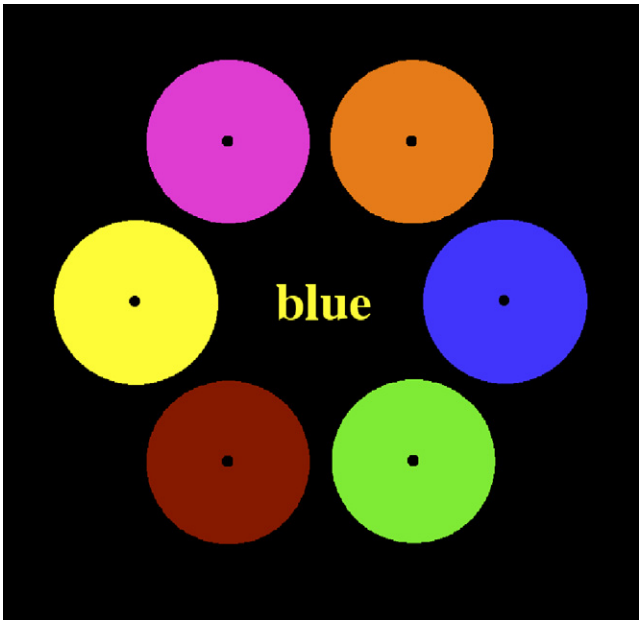


Fig. 1. A stimulus display like those used for the visual search task in all three experiments. The correct response in this case is to gaze or point at the blue circle (on the right). The yellow circle (at left) represents an irrelevant text color match. The colors of the response locations vary from trial to trial. (For interpretation of the references in colour in this figure legend, the reader is referred to the web version of this article.)

highlighted with a white outline. If the correct target was selected (the color named by the word), the screen went blank after 100 ms. If the wrong circle was selected, that circle remained highlighted for 250 ms before the display was erased and an error tone sounded. If three or more errors occurred within a span of 20 trials (including dummy recovery trials), a visual warning message would instruct the participant to avoid error.

2.1.3. Design and procedure

Each observer participated in one block of 192 trials with the target word printed in conflicting colors and another block of 96 trials with the target word printed in gray (note that Durgin, 2003, did not include a neutral condition). Block order was counterbalanced between observers. From an existing set of 8 colors (red, blue, green, brown, orange, purple, pink, and yellow), four were chosen at random as the target colors for a given observer, and only those four were presented as words for that observer. The 192 conflict trials were factorialized, meaning that each color word was presented with its corresponding color patch in each of the six locations and with the print color varied such that half the time it was from within the set of target colors, and half the time it was present among the six colors presented in the array ($4 \times 6 \times 2 \times 2$). This basic design of 96 trial types was replicated twice to compose the 192 conflict trials. In the no conflict, gray text, condition, each of the four target colors appeared as targets in each of the six locations four times in random order.

There were 24 warm up trials before each block, and each error trial was followed by an inserted random recovery trial, so the total number of trials for each participant was about 350 when few errors were made though it averaged over 400 because of the high numbers of error trials. An experimental session typically took 20–25 min to complete.

2.1.4. Analysis

Two separate analyses were conducted. The principal analysis was of response latencies (RT), the total time between when the target word was first presented and when the center of gaze entered a target color patch. Medians of correct response trials were analyzed for effects of overall condition (conflict vs. neutral) and, within the conflict trials, for effects of Set and Match. Error rates are also reported.

The second major analysis was of spatial aspects of gaze-response errors. However, this analysis will be presented in conjunction with the gaze results of Experiment 2 because of similarities between the patterns of gaze patterns in the two experiments.

2.2. Results and discussion

2.2.1. Latency data

Data from correct trials was used to compute median gaze arrival latencies for each trial type for each subject. The latency and error data for the four conflict conditions and the neutral condition are shown in Table 1. Conflict trials were much slower overall (586 ms) than neutral trials (540 ms), $t(28) = 3.04$, $p = 0.0051$. Contrary to our original expectation, a 2 (Target Set) $\times$ 2 (Matched Foil) repeated measures ANOVA conducted on the gaze latencies of correct response conflict trials detected no main effect of the presence of a Match, $F(1,28) < 1$. However, conflicting print colors, which belonged to the set of possible targets (Set) produced reliably longer RTs ($M = 594$ ms) than those that did not ($M = 579$ ms), $F(1,28) = 12.6$, $p = 0.0014$.

The gaze data (i.e., gaze errors), do show evidence of Match effects, though these will turn out to be a fairly minor component in our gaze analysis below. Consistent with previous studies (Durgin, 2003), error responses were most frequent for trials in which the distracter color was both in the set of target colors and had a matched patch among the responses. Specifically, there was a reliable interaction of Set and Match in the error data, $F(1,28) = 4.53$, $p = 0.042$, which licensed the pair-wise comparisons of all conditions. Although these differences

Table 1
Response latency and error rates with standard error values by distracter type in Experiment 1

	In-Set		Out-of-Set		
	Matched	Unmatched	Matched	Unmatched	Neutral
Gaze latency (ms)	595 ± 23	593 ± 22	574 ± 20	584 ± 23	540 ± 17
Gaze error (%)	21.5 ± 2.2	15.6 ± 1.9	17.0 ± 1.9	15.1 ± 1.7	14.8 ± 1.5

Table 2
Response latency (ms) and error rates (%) with standard error values by target location for neutral and for conflict blocks in Experiment 1

	Left	Up-Left	Up-right	Right	Low-Right	Low-left
Neutral (ms)	524 ± 15	556 ± 18	533 ± 18	494 ± 14	546 ± 18	564 ± 18
Neutral (%)	14.7 ± 2.2	17.7 ± 3.1	16.2 ± 2.5	9.9 ± 1.4	14.2 ± 2.3	20.0 ± 2.7
Conflict (ms)	580 ± 22	605 ± 23	581 ± 22	548 ± 21	611 ± 26	641 ± 26
Conflict (%)	15.1 ± 2.1	14.3 ± 2.1	15.2 ± 1.6	13.8 ± 2.0	17.0 ± 2.2	21.0 ± 2.3

were consistent with published error differences, the overall error rate was quite high, independent of condition.

To ensure that the latency results were not simply an artifact of the high-error rates overall, the latency data of the 14 participants with error rates below 15% were analyzed separately. Again, there was a reliable (15 ms) effect of Set, $F(1,13) = 10.69$, $p = 0.0061$, and no effect of match, $F(1,13) < 1$. The effect of Set in the high-error group, though of the same average magnitude (14 ms), was only marginally reliable, $F(1,14) = 4.20$, $p = 0.060$ – presumably because of greater variability.

Median response latencies and error rates were also computed with respect to the spatial location of the target, and are shown in Table 2. Errors and RTs were each minimized when the target was to the right, both for neutral and for conflict trials, which is consistent with the rightward distribution of attentional resources during reading. Because response times include both perception and action, the rightward advantage would also be consistent with a bias toward rightward eye-movements during reading. However, analysis of gaze errors suggests a somewhat different spatial bias for gaze.

2.2.2. Gaze errors

The very high-error rate in this experiment appeared to derive from failures to control gaze. Based on pilot experiments in which error rates were quite high, we had modified the displays to aid gaze control and gaze awareness by providing a central black mark in each color patch to guide fixation, by high-lighting the gazed-at targets to provide explicit feedback, and by providing salient error warnings when error rates surpassed 15% during any block of 20 trials. The gaze errors seemed to derive primarily from unconscious gaze activities. Many participants protested that they had not shifted their gaze when they actually had. (Frequent recalibrations of the eye tracker were

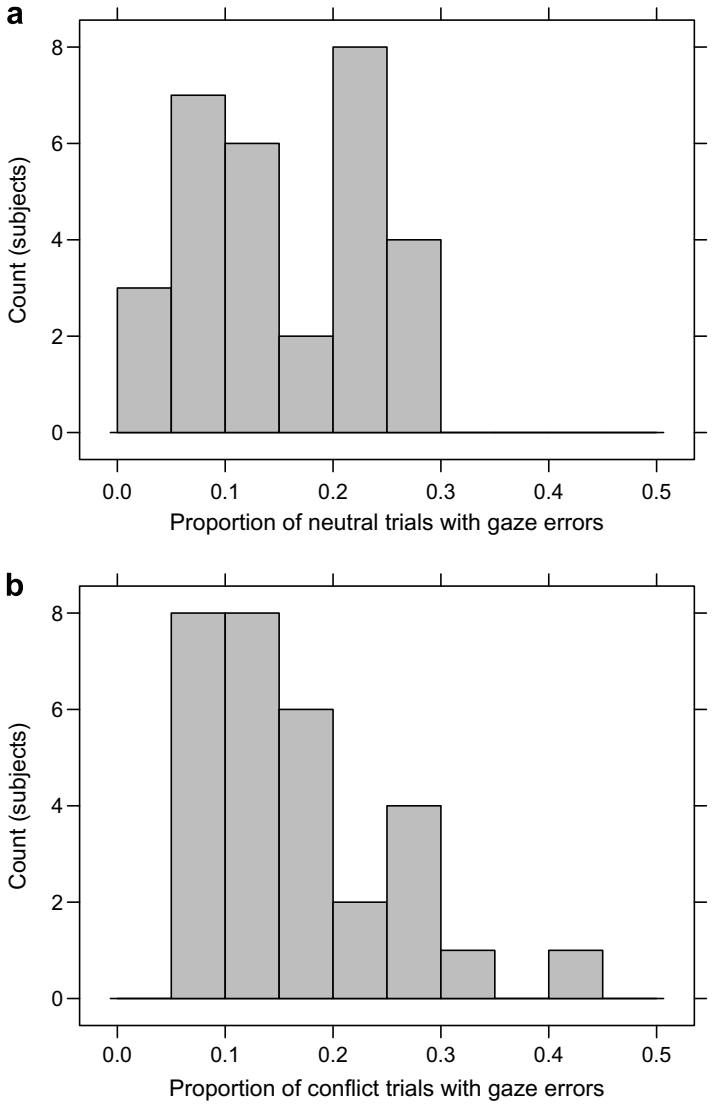


Fig. 2. Histogram of gaze error frequencies in Experiment 1 for blocks of conflict trials (top panel: Stroop word) and blocks of neutral trials (bottom panel: color word printed in gray). Most of the errors are not due to Stroop-like interference.

undertaken in some cases to ensure that gaze calibration was maintained, but this was never the problem.) Histograms of gaze error frequency (excluding practice and recovery trials) are shown in Fig. 2 for conflict trials and for neutral trials. Although the average error rate for neutral trials (14.8%) is reliably less than that for conflict trials (17.3%), $t(28) = 2.38$, $p = 0.024$, the overall magnitude of error overshadows this difference. Note that error rates for the original pointing task (Durgin, 2003) were typically 1–4% for conflict trials. It is to be emphasized that in the present paradigm, any saccade into a target region counted as a response even if fixation was extremely brief. For further discussion of this measure, see the Appendix.

Two global spatial patterns were present in the gaze error data. Gaze errors tended to be adjacent to the correct target location, consistent with a coarse-to-fine scheme for visual search (e.g., Rao, Zelinsky, Hayhoe, & Ballard, 1996, 2002; Zelinsky, Rao, Hayhoe, & Ballard, 1997). In this respect the errors tended to show evidence of partial information. Second, the gaze errors showed an overall spatial bias to the left and upper-left locations. Given the evidence that the right location was somewhat privileged overall, the upper-left bias might reflect an optimal information foraging strategy in the absence of success to the right. Because gaze control is normally handled without awareness, we suspected that unconscious gaze strategies might be similar when gaze was not used as a response. We therefore conducted a second experiment in which gaze was monitored during a pointing version of the task to see what kinds of gaze patterns were evident during the pointing task. Because they were indeed quite similar, a complete spatial analysis of first-gaze patterns for Experiments 1 and 2 will be presented together below.

3. Experiment 2: Incidental gaze during the pointing task

In this experiment we replicated Experiment 1, except that participants responded by pointing to the color patch with a mouse cursor as in Experiment 1 of Durgin (2003). The response patches in the present experiments were much larger than those used by Durgin and were spatially separated so that gaze location would be unambiguous. Other slight differences in procedure were required (drift corrections before each trial) because of the need to keep the eye-tracker calibrated. In addition to the collection of gaze data, Experiment 2 therefore also serves to check whether the Set and Match effects of previous studies will be replicated with the present set-up and stimulus configuration.

3.1. Methods

The design, apparatus, and displays were identical to those of Experiment 1. Only the method of response was changed to pointing with a mouse. Eye-movements were still recorded.

3.1.1. Participants

Thirty Swarthmore College undergraduates were paid for their participation. All had normal color vision and were unaware of the specific hypotheses being tested. None had previously participated in Stroop experiments.

3.1.2. Changes to the procedure

On each trial the participant had to first move the mouse cursor into the central fixation square. Then, while gazing at the fixation square, the participant pressed the space bar to initiate the trial (and correct for any drift in the eye-tracker). After a short delay, the mouse cursor and fixation mark disappeared and were replaced by the Stroop word and the six target patches. The mouse cursor remained invisible (so as not to mask the word) until it was moved out of the (virtual) fixation square. The presence of the mouse cursor in one of the response circles was counted as a response. A ballistic motion of the mouse into or through any response circle produced the same feedback used in Experiment 1: the circle was outlined in white and error feedback was given.

3.2. Results and discussion

3.2.1. Pointing data

The mean median latencies are shown in Table 3. As expected, conflict trials were much slower overall (671 ms) than neutral trials (620 ms), $t(29) = 4.35$, $p = 0.00015$. A 2 (Target Set) × 2 (Matched Foil) repeated measures ANOVA conducted on the gaze latencies of correct response conflict trials showed that text colors from the set of used words used caused longer latencies (by 23 ms), $F(1, 29) = 38.52$, $p < 0.0001$. However, the effect of Match (11 ms) was only marginally reliable $F(1, 29) = 3.06$, $p = 0.091$. These findings roughly replicate the results of Durgin (2003). Similarly the error data showed a reliable interaction between Set and Match, $F(1, 29) = 9.89$, $p = 0.0038$, that reflected a stronger effect of matches that were from within the set of color words used. This is consistent with Durgin (2003): As mentioned above, pointing errors are more likely in this task when a Match is present

Table 3
Response latency and error rates with standard error values by distracter type in Experiment 2

	In-Set		Out-of-Set		
	Matched	Unmatched	Matched	Unmatched	Neutral
Latency (ms)	684 ± 17	679 ± 16	669 ± 16	653 ± 15	620 ± 12
Error (%)	3.9 ± 0.6	1.0 ± 0.3	2.3 ± 0.5	1.5 ± 0.4	2.1 ± 0.3

Table 4
Response latency (ms) and error rates (%) with standard error values by target location for neutral and for conflict blocks in Experiment 2

	Left	Up-left	Up-right	Right	Bot-right	Bot-left
Neutral (ms)	609 ± 13	618 ± 12	642 ± 16	598 ± 12	630 ± 16	646 ± 14
Neutral (%)	1.9 ± 0.6	1.9 ± 0.7	2.1 ± 0.5	2.5 ± 0.8	2.5 ± 0.8	1.9 ± 0.7
Conflict (ms)	667 ± 15	674 ± 20	682 ± 19	635 ± 17	683 ± 18	697 ± 16
Conflict (%)	2.5 ± 0.6	1.1 ± 0.3	2.5 ± 0.7	1.5 ± 0.4	2.1 ± 0.4	3.4 ± 0.7

because other kinds of pointing error are rare, and this, combined with a strong influence of Set, leads to a statistical interaction between Set and Match in the error data.

As in Experiment 1, we also computed median response latencies and error rates by target location. These are shown in Table 4. Latencies are again shortest for targets at the right, but the patterns of error in the conflict conditions also suggest an advantage for the upper-left location and a relative disadvantage for the lower left location. Note that the upper-left target error advantage was not present in Experiment 1. Because Experiment 2 allows incidental eye-movements without overt penalty, the upper-left advantage in error reduction could correspond to the effects of an eye-movement bias in that direction. That is, although information from the right has a clear initial advantage, an advantage in the upper left seems to follow. In the conflict conditions, this seems to leave the lower left region subject to greatest neglect.

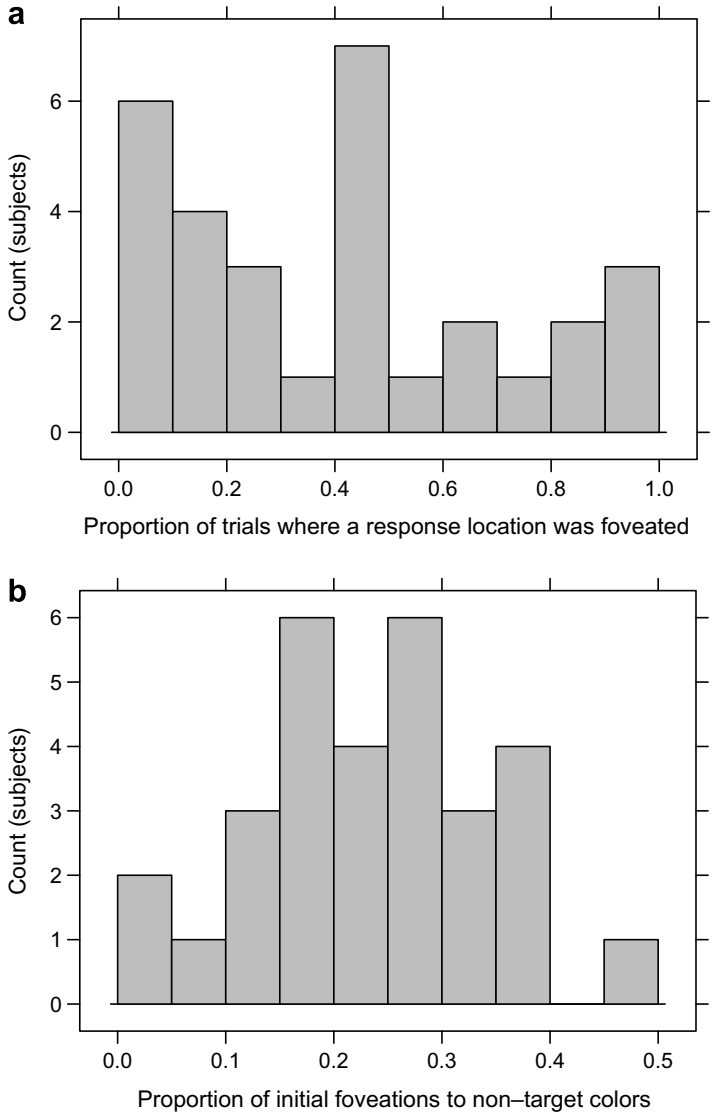


Fig. 3. Histograms showing the proportion of trials on which individual participants foveated response patches in Experiment 2 (top) and the proportion of those foveations that were initially to non-target locations (bottom).

3.2.2. Gaze frequencies

Performing the pointing task does not require the movement of gaze, and some participants rarely moved their eyes, while others foveated the response locations quite frequently. A histogram of these frequencies is shown in Fig. 3. Half of the participants moved their eyes to at least one of the response circles on at least 44% of the trials. A median split of the participants based on these gaze frequencies was used to create two sub-groups of 15 participants. The patterns of RT as a function of distracter type were similar for both sub-groups (Set was reliable for both, and of the same magnitude). Those who made fewer eye-movements had marginally shorter response latencies (by 46 ms) during the neutral blocks of trials than those who made eye-movements more frequently, $t(28) = 1.97$, $p = 0.059$. Error patterns were less pronounced for those who made fewer eye-movements (no reliable effects of distractor type) than for those who made many eye-movements, for whom there was a highly reliable interaction between Set and Match, $F(1,14) = 9.95$, $p = 0.0070$, and a 4.6% error rate for matched distracters from the word set.

We have seen similarities between the results of Experiments 1 and 2 as well as a few differences. In both experiments there was a Set effect in the latency data and an interaction effect in the error data, reflecting a Set effect among false matches. In both experiments, targets presented to the right seem best processed, and targets to the lower left seem worst processed. In both experiments there is a lot of quantitative variation between participants in the use of gaze. In Experiment 1 this is reflected in the frequency of gaze-response errors, whereas in Experiment 2 it is captured in the absolute frequency of eye-movements. Although the requirement to use gaze as a response likely altered people's gaze behavior to some degree, it seems reasonable to compare those who move their eyes frequently in Experiment 2 to those who made frequent inadvertent gaze errors in Experiment 1.

4. Spatial analysis of initial gaze behavior in Experiments 1 and 2

Because the majority of gaze errors (saccades to a response location other than the correct target) in both experiments seemed to occur independent of whether text color conflicted with the printed word, we focused our analysis on the spatial locations of the errors. So as to maximize the absolute number of gaze error trials for analysis, recovery trials and all but the first ten practice trials were included in the analysis of gaze errors.

In the analyses below we will show that the explicit errors in Experiment 1 are very similar to the implicit "gaze errors" of Experiment 2. That is, if we look at the first response location foveated on each trial of Experiment 2, we can define gaze errors as first target fixations that were not at the correct response color (ignoring refixations that did not end on a target location; see the Appendix for more detail). These first-gaze errors follow spatial patterns that are remarkably similar across the two experiments. We will suggest that these gaze patterns reflect unconscious information gathering strategies that were (evidently) relatively impenetrable to the error feedback given in Experiment 1.

4.1. Selection of participant data from Experiment 2

Because many participants in Experiment 2 did not produce large numbers of eye-movements, we restricted our analysis to the 15 from that experiment who moved their eyes into one of the response regions on at least 44% of trials (median split). We needed a large number of eye-movements for analysis because most shifts of gaze, even in Experiment 2, were simply to the correct target itself and were therefore uninformative about strategy. Moreover, these 15 participants were also the most prone to gaze "errors" when they did move their eyes. That is, on trials in which they shifted gaze, their first gaze was more likely to miss the target color (30%) than the first gaze of participants who rarely shifted gaze (16%), $t(28) = 4.46$, $p = 0.00012$. Gaze errors represented an average of 20.8% of the total trials for the 15 frequent-gaze participants, which was similar to the overall gaze error rate in Experiment 1.

4.2. Target proximity

For both experiments, locations of gaze error were governed by two spatial factors. One factor was relative to the target location and one was absolute. The first spatial factor was proximity to the target. This is graphically depicted in Fig. 4 by a plot of first gaze frequency for the six relative target positions, collapsed so that absolute target location is always depicted as up. Gaze errors in Experiment 1 are more often made to regions adjacent to the target (51.4%) than would be expected by chance (40%), $t(28) = 6.37$, $p < 0.0001$. A similar pattern is evident for Experiment 2, $t(14) = 4.98$, $p = 0.0002$. This indicates that gaze movement on error trials was often influenced by actual target position, consistent with coarse-to-fine models of visual search (e.g., Rao et al., 1996, Rao, Zelinsky, Hayhoe, & Ballard, 2002; Zelinsky et al., 1997).

4.3. Upper-left bias

More surprising, however, is the absolute spatial bias for gaze errors, as shown in Fig. 5. These plots show the relative frequencies of first gaze locations for gaze error trials in the two experiments (Experiment 1 on the left). The two plots are essentially identical. In Experiment 1, gaze errors tended to be toward the upper left (22%) of the search display at a rate reliably greater than chance (16.7%), $t(28) = 2.78$, $p = 0.0097$. The same statistic in Experiment 2 (23.5%) is marginally reliable, $t(14) = 1.97$, $p = 0.069$. In addition, gaze errors to the lower right were less likely than chance both in Experiment 1 (9.9%, $t(28) = 5.05$, $p < 0.0001$) and Experiment 2 (10.7%,

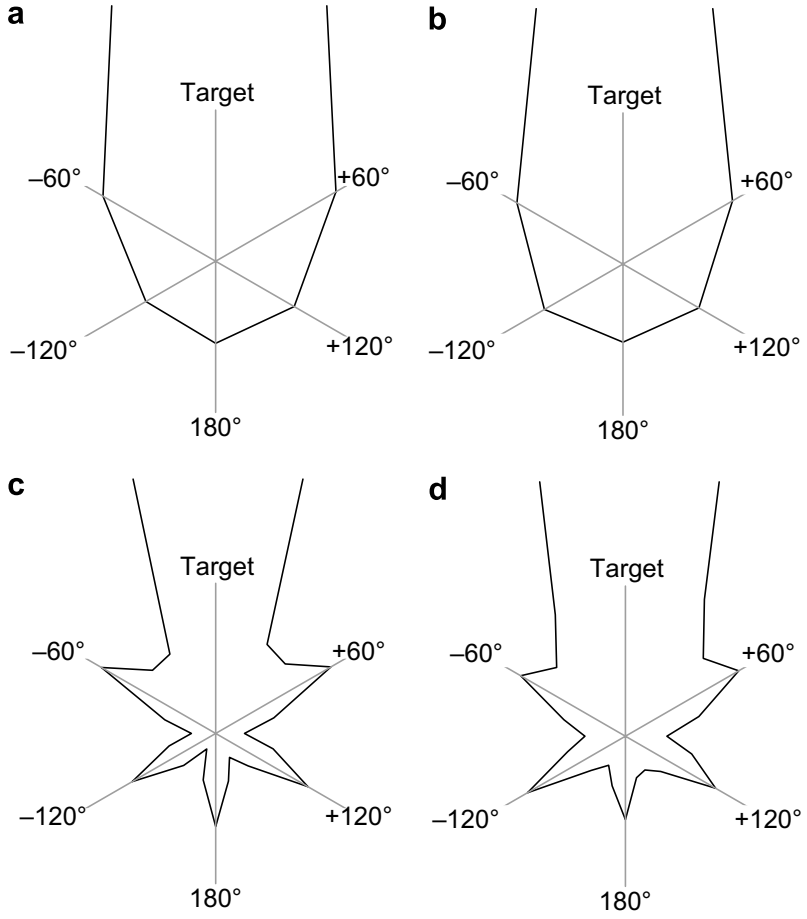


Fig. 4. Relative spatial biases in first gaze behavior. The upper panels show relative frequency of initial response-patch foveation relative to target location (depicted as up) for Experiments 1 (a) and 2 (b). The lower panels are radial histograms of the angles (binned in 15° increments, relative to target location, depicted as up) of all first saccades of at least 2° for Experiments 1 (c) and 2 (d). In both experiments first gaze errors tend to be proximal to the target location. Radial plots created using plotrix in R (Lemon, 2007; R Development Core Team, 2007).

$t(14) = 3.30$, $p = 0.0053$). The additional apparent gaze bias toward the left position of the display (20.6%) was only marginally reliable in Experiment 1, $t(28) = 1.96$, $p = 0.060$, though the results of Experiment 2 (22.1%) also show a trend for a leftward bias.

Overall, the spatial biases for gaze errors in both sets of data were highly consistent with one another; both showed a bias toward the upper left and away from the lower-right portion of the display. It therefore appears that the unconscious gaze strategies used in this visual search task are fairly stable across conditions, whether gaze is unconstrained (Experiment 2) or is controlled and meant to be used exclusively for response (Experiment 1).

Levy-Schoen (1974) has previously reported upward (see also Dark, Vochatzer, & VanVoorhis (1996)) and upper-left gaze biases, although Findlay (1980), using a salience task, reported a rightward bias. These findings are both consistent, in fact, with the present data because there is clearly an initial rightward biasing of attention (see also Levy-Schoen, 1969), but, if the correct target is not at the right, there is often a movement of gaze to the upper left that seems to be part of a cognitive foraging strategy. In Experiment 2, where eye-movements were optional, targets that were presented to the right were more likely to receive fixation than any other, as illustrated in Fig. 6. This rightward bias in the accurate case is consistent with Findlay's report, and may reflect a well-documented attentional bias in reading (e.g., McConkie & Rayner, 1975; McConkie & Zola, 1987). The fact that there was no corresponding increase in accurate-gazes to the upper left is consistent with the idea that such gazes were not guided as much by the information in the upper left as by the absence of information to the right or elsewhere.

4.4. Additional factors affecting gaze errors

The three non-spatial sources of error that we have closely examined are (1) colors in the Set (had appeared as targets on other trials), (2) colors similar to the color named by the target word, and (3) sensory matches to the (irrelevant) color in which the target word was printed. We will describe in detail only the incidental gaze data from Experiment 2, the more naturalistic task. Similar patterns exist in the data of Experiment 1, as may be observed in Table 5.

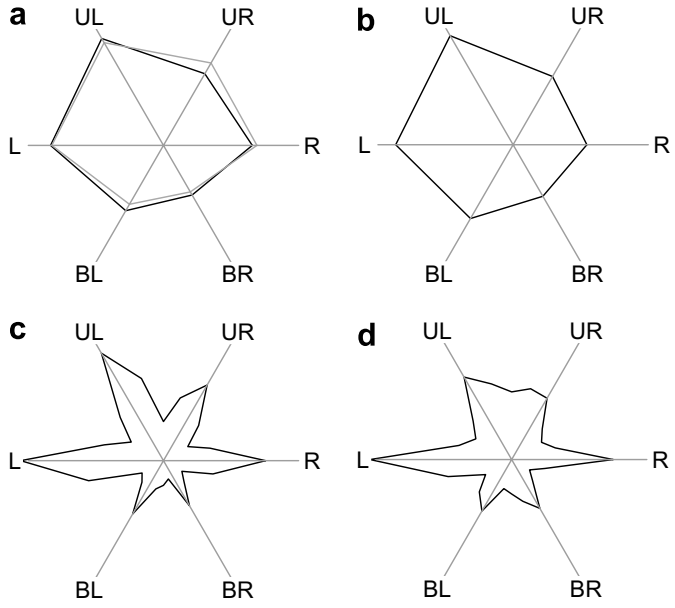


Fig. 5. Absolute spatial biases in first gaze behavior for Experiment 1 (Panel a) and Experiment 2 (Panel b). When the target color is not fixated first, the relative frequency of first gaze locations is biased to the upper left of the display. Full data (gray) and 15 most error prone participants of Experiment 1 (black) are shown. Panels c (Experiment 1) and d (Experiment 2) show radial histograms of the direction of the first non-target-directed saccade longer than 2° for each trial across all subjects.

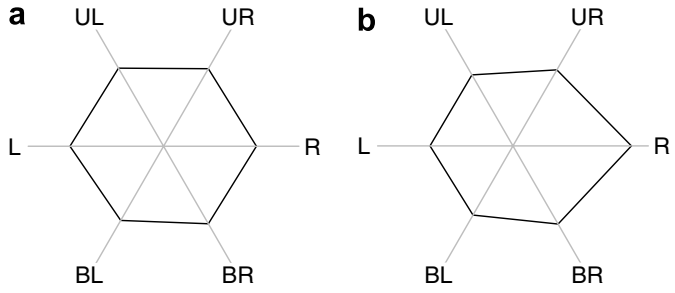


Fig. 6. Relative frequency of first gaze accuracy as a function of target location for Experiments 1 (a) and 2 (b). Because a movement of gaze was required in Experiment 1, the rightward attention bias evident in Experiment 2 was probably masked by the predominance of accurate overt responses in Experiment 1.

4.5. Color from the response set

Color identity played a powerful role in directing fixations. Although only 2 of the 5 possible non-target response locations (40%) were filled with colors that had been used as target words on other trials, non-target first gaze was more likely to go to color patches that had been used as words (Set, 55%) than expected by chance, $t(14) = 7.83$, $p < 0.0001$. Some of this reflected recent priming: If a color that had been the target color on the just-previous trial was available as an error response, it was more frequently foveated than was the alternative In-Set foil (59% vs 41%), $t(14) = 2.50$, $p = 0.025$. This one-back effect did not account for the entire Set effect on error gazes (i.e., on average, it can account for five of the 19 error saccades to In-Set foils that are above chance levels for error saccades based on Out-of-Set foil foveation frequencies). The idea that recently used representations are primed is fundamental to accounts of Set effects. Note that error saccades were also marginally more likely than chance (17%) to visit the absolute spatial location of the target of the previous trial (20%), $t(14) = 2.00$, $p = 0.065$, though this accounted for only about two error saccades overall per subject (2%).

4.6. Similar colors

Gaze often went to colors that were similar to the target color. Of 28 possible color pairs we identified seven pairs (e.g., purple and pink, orange and yellow) that were relatively similar. Similar-color response locations accounted for 41% of gaze errors, which was reliably greater than chance (25%), $t(14) = 5.36$, $p = 0.0001$.

4.7. Color matches

A response patch matching the text color was present on roughly 1/3 of all trials (i.e., half of conflict trials and none of the neutral trials). Half of these were in the set of words used and half were not. Based on each person's probability of first fixating a non-target color from the word Set (p(Set|error)), we calculated the chance probability for each subject of gazing in error at an In-Set Matched response patch. The measured frequencies of fixating Match targets in error when the match color was from the Set (7.2) were reliably higher than predicted by the Set effect alone (4.4), $t(14) = 4.15$, $p = 0.00098$. Similarly, the measured frequencies of fixating non-Set Match targets in error (3.6) were reliably higher than expected by chance for the non-Set case (1.8), $t(14) = 3.32$, $p = 0.0051$. Evidently, the effect of Match was strong both for colors within the Set and those not in the Set, nearly doubling the error frequencies in each case.

5. Analysis of gaze vectors across both experiments

So far we have considered gazes that the Eyelink registered as entering a target region (a fairly conservative approach, as shown in the Appendix). As a check on this first analysis, we conducted a new analysis in which we considered the first saccade that exceeded 2° in length on each trial. (Shorter initial saccades are common because of refixations of the target word during initial encoding, but such refixations of the target word are not of interest here.) For each trial in each of Experiments 1 and 2, we used R (R Development Core Team, 2007) to compute the direction and magnitude of each saccade and, based on the first saccade on each trial that exceeded 50 pixels (2°), we categorized the trial as having a saccade toward one of the six possible target directions (according to its angle). As in

Table 5
Summary gaze statistics for both first large saccade (Vector) and first response-location foveation (Gaze) supporting five influences on gaze in Experiments 1 and 2

A. Counts of saccades toward (or foveations of) response patches

	N	Total trials	Saccades	Gaze accurate	Gaze error
Expt 1 vector[a]	29	407[b] ± 8[c]	407 ± 8	286 ± 6	121 ± 12 (30%)
Expt 1 gaze[d]	29	403 ± 8	403 ± 8	334 ± 1	69 ± 8 (17%)
Expt 2 vector	30	334 ± 1	230 ± 18	130 ± 10	100 ± 10 (30%)
Expt 2 gaze	15[e]	333 ± 1	222 ± 18	152 ± 11	70 ± 8 (21%)

B. Relative spatial biases in error saccades (target proximity)

	Relative spatial location (chance likelihood)		
	Adjacent (40%)	Two-Away (40%)	Opposite (20%)
Expt 1 vector	60 ± 6 (50%)[f]	41 ± 5 (34%)	19 ± 2 (16%)
Expt 1 gaze	36 ± 4 (51%)	23 ± 3 (33%)	11 ± 1 (16%)
Expt 2 vector	51 ± 5 (51%)	35 ± 4 (35%)	14 ± 2 (14%)
Expt 2 gaze	34 ± 4 (48%)	25 ± 3 (36%)	11 ± 1 (15%)

C. Absolute spatial bias in error saccades (upper and left spatial bias)

	Spatial location or direction of saccade					
	Left	Up-left	Up-right	Right	Bot-right	Bot-left
Expt 1 vector	27.5[g]	27.3	20.2	20.2	10.9	12.5
Expt 1 gaze	14.8	15.8	12.1	12.0	6.2	8.2
Expt 2 vector	23.0	20.1	17.4	17.0	10.4	12.5
Expt 2 gaze	15.6	15.8	10.0	10.3	7.7	10.7

D. Absolute color bias in error saccades (In-Set colors)

	In-Set (40%)	Out-of-Set (60%)	Previous-target[h]
Expt 1 vector	74 ± 8 (61%)	36 ± 4 (39%)	(26 ± 4 > 16 ± 2)
Expt 1 gaze	45 ± 6 (65%)	24 ± 4 (35%)	(17 ± 3 > 9 ± 1)
Expt 2 vector	55 ± 5 (55%)	45 ± 5 (45%)	(20 ± 2 > 13 ± 2)
Expt 2 gaze	39 ± 4 (55%)	31 ± 4 (45%)	(14 ± 2 > 9 ± 1)

E. Bias toward colors similar to target color

	Mean count (chance would be 25%)
Expt 1 vector	41 ± 5 (35%)
Expt 1 gaze	29 ± 3 (42%)
Expt 2 vector	37 ± 4 (37%)
Expt 2 gaze	28 ± 3 (41%)

F. Bias toward colors matching the distracter color when present

	Match trials	Error gazes	To match (20%)
Expt 1 vector	134 ± 3	43 ± 5 (32%)	15 ± 2 (34%)
Expt 2 gaze	132 ± 3	26 ± 3 (20%)	10 ± 2 (39%)
Expt 2 vector	108 ± 1	34 ± 4 (31%)	11 ± 1 (33%)
Expt 2 gaze	108 ± 2	25 ± 4 (23%)	11 ± 2 (43%)

[a] Vector angles of first saccade of at least 50 pixels on each trial.
[b] Includes trials terminated by blinks, for which saccades were recorded.
[c] Standard errors of the means are shown.
[d] Foveations of response locations.
[e] Fifteen are from upper half of median split on error saccade count.
[f] Mean count per subject. Parenthetic number represents percent of error saccades.
[g] Mean count per subject.
[h] For trials where there was an error saccade to an In-Set color and one of the In-Set distractors was the target color of the previous trial, the number on the left reflects the average number of error saccades to that color, which is always greater than that to the other In-Set color (chance odds would make them equal). These differences do not account for the Set effect overall, but do indicate that the Set effect includes a short-term component (recently search-for colors).

our earlier analysis, such saccades were considered "errors" if they went toward a response location other than the correct one. Data from all 29 subjects from Experiment 1 were included in one analysis, while the data from all 30 subjects from Experiment 2 were included in a second analysis. The results of these analyses will not be presented in

detail, though full summary statistics for all analyses are given in Tables 5A–F. They support the foregoing analyses.

5.1. Summary of gaze error patterns

By all metrics, gaze errors (first fixations on color patches other than the target) occurred on a minority of trials, and showed evidence of being informed by actual target location (proximity) as well as by actual target color (color similarity effects). These effects provide evidence of partial information from the present trial guiding eye-movements, even when they are in error. Such partial information effects are well known (e.g., Findlay, 1997). There was also evidence that perceptual grouping (Match effects) as well as history (Set effects) contaminate the choice of gaze locations (see also Christie & Klein, 1995; De Graef, 1998). All of these findings are consistent with the thesis that selecting a target for gaze may be triggered prior to full information gathering and that this is probably adaptive in most contexts (Araujo, Kowler, & Pavel, 2001).

Although gaze behavior during visual search has received much scrutiny (Belky & Motter, 1998; Findlay, 1997; Findlay, Brown, & Gilchrist, 2001; Motter & Belky, 1998; Rao et al., 2002), there are few reports of absolute spatial biases, though there are very strong proximity effects (e.g., Araujo et al., 2001). On top of all these sources of information that affect first fixation in the present experiments, there is an additional bias toward the left and upper left of the display, which is not directly explained by stimulus information. This bias seems consistent with patterns of reading from the upper left, that is, with a deeply ingrained habit of starting scanning from the upper left.

Although the gaze errors in Experiment 1 were somewhat costly, it is clear that a large number of people in the experiment were unable to fully control their gaze. The failure to suppress information-based strategies is understandable because these are essentially false alarms, but the failure to suppress the upper-left bias appears somewhat surprising because these seem more like information-less guesses. However, the feedback provided in Experiment 1(the trial was terminated) may not have served as interpretable feedback for the cognitive routines involved. Clearly the upper-left gaze bias could be regarded a functional exploratory strategy in Experiment 2. Given that response times are most efficient when the target is to the right and given that the spatial distribution of targets is uniform, there is no disadvantage to a biased search strategy away from the rightward location under normal circumstances.

In order to test the malleability of the upper-left gaze bias, we sought to set up an experimental context in which gaze was free to move, but the effectiveness of the upper-left gaze bias could be manipulated. This manipulation turned out to affect not only spatial gaze patterns, but also response latency patterns, suggesting that it interacted with participants' choice of cognitive strategy.

6. Experiment 3: Effect of spatial biases of target placement

Although the upper-left gaze bias had seemed impervious to error feedback in Experiment 1, we reasoned that gaze might be more easily trained in a more naturalistic task where there was a positive environmental structure to be learned (Geng & Behrmann, 2002). Specifically, we sought to test whether biasing the spatial location of the target would affect spatial biases in gaze. As we will show, those who were exposed to a spatial bias that reinforced the pre-existing gaze bias (targets were predominantly presented to the upper left) seemed to engage a completely different cognitive strategy than those who were exposed to an opposing spatial bias. The reinforcing bias seemed to encourage a (serial) matching strategy (Strategy 2) whereas the opposing bias seemed to encourage a parallel search strategy (Strategy 1). The change in cognitive strategy is evidence that the spatial bias manipulation mediated strategy choice (sensory coding and parallel search vs. serial matching) more strongly than strategy execution (revision of gaze bias direction), though changes in strategy execution are also evident.

6.1. Method

The method was similar to that of Experiment 2, with the exception of the introduction of spatial biases. For those in the Upper-Left Bias condition (ULB), the target color appeared most often in or near the upper-left location, thus reinforcing the upper-left gaze bias. For those in the Lower-Right Bias condition (LRB), the probabilities were switched so that target colors appeared most often in or near the lower-right location. As a result, the pre-existing upper-left gaze bias was made highly dysfunctional in the LRB condition.

6.2. Participants

Twenty-seven Swarthmore College undergraduates from an introductory psychology course participated in partial fulfillment of a course requirement. Fourteen of the participants were assigned to the LRB condition, and the remaining 13 to the ULB condition. All were naïve to the purpose and design of the experiment.

6.3. Design and procedure

The only substantive change from the basic methods of Experiment 2 was that target location on each trial was established randomly according to a weighted probability function. The most favored location (either upper left or lower right, depending on condition) had a 35% chance of being selected on a given trial, and immediately adjacent locations each had a 20% chance. Conversely, the opposite location had only a 5% probability of having the target, and its adjacent positions each had a 10% chance of

selection. The total number of trials and the design were otherwise identical to Experiment 2.

6.4. Results and discussion

The manipulation of gaze by means of the spatial bias was quite effective. Fig. 7 shows the distribution of "error" gazes (first gazes that did not go to the target) for the two conditions plotted against the targets' spatial probabilities. It seems quite clear that gaze patterns, in this experiment, were altered to appropriately reflect target probabilities.

Before providing further analysis of the gaze behavior, let us consider the results of the main experimental task, which was to point to the color indicated by the word. As in previous experiments, a repeated measures ANOVA was used to analyze the latency data from the conflict conditions with 2 within-subject factors being Set and Match, but this time, a between-subject factor (Bias) was also included. Bias interacted marginally with both Match, $F(1,25) = 4.09$, $p = 0.054$, and Set, $F(1,25) = 4.07$, $p = 0.055$. Because of these dual sources of evidence that Bias was interacting with the two within-subject factors, separate ANOVAs were conducted for the two Bias conditions.

For the 13 participants in the ULB condition, which reinforced spatially biased default gaze strategies, there was no reliable effect of distracter color type (Set), $F(1,12) < 1$, n.s. However, trials with peripheral matching foils (797 ms) were substantially slower than those without (761 ms), $F(1,12) = 20.3$, $p < 0.001$. This is notable because match effects in previous experiments, including those in this paper, have never exceeded about 15 ms, whereas these were twice that. Moreover, in previous reverse Stroop experiments (Durgin, 2003), the Set effect was larger than the Match effect, whereas this group of participants shows no Set effect whatsoever. It therefore appears that reinforcing the spatial gaze bias found in Experiments 1 and 2 has altered task behavior in a way that may have completely changed the choice of cognitive strategy for the task.

Conversely, for the 14 participants whose default gaze bias had been opposed (those in the LRB condition), the same analysis revealed a pattern of response latencies quite similar to those reported by Durgin (2003). Specifically, latencies were longer when the distracter color was from the target Set (777 ms) than when it was not (745 ms), $F(1,13) = 30.6$, $p < 0.0001$. This is the same magnitude of cost found in previous studies (~30 ms; e.g., Durgin, 2003). Trials where peripheral color patches matched the distracter text color (769 ms) were also reliably longer than those which did not (753 ms), $F(1,13) = 5.82$, $p = 0.031$. Again the magnitude of this effect is nearly identical to the 14 ms match effect found by Durgin (2003).

If the effects of biasing target locations had been simply symmetrical, we should not expect to see such clear differences between the two conditions in their response latencies. Although gaze patterns did adapt to the contingencies in one sense (as shown in Fig. 7), there was a trend for fewer gazes to be made in the LRB condition overall. The average frequency of trials involving a movement of gaze in the ULB condition was 47% compared to only 35% in the LRB condition. A histogram of gaze frequencies shown in Fig. 8, shows that many of those in the ULB condition ended up moving their gaze extremely frequently (eight of 13 moved their gaze on more than half the trials) compared to those in the LRB condition (where only four of 14 participants moved their gaze on more than half the trials).

The latency data are consistent with the interpretation that the original upper-left bias is part of an unconscious search strategy (Strategy 2) that is impervious to Set effects because it involves quickly storing the visual word, and not the text color in which it is printed. This strategy shows no effects of the identity of the distracter color because the distracter color does not interfere with the formation of the verbal representation that guides search. Instead, search is probably guided by a verbal code and the colors of response locations would need to be serially translated into verbal colors and tested for a match with the target word. When targets are biased to appear in the upper-left location, this similarly-biased serial strategy is extremely successful and presumably becomes predominant by being reinforced. Matching foils may produce a cost when this strategy is employed either because false evidence of a match can come from noting a perceptual match along the irrelevant dimension, or simply by attracting spatial attention.

The latency data from the LRB condition suggests that target location biasing seems to have affected cognitive strategy choice rather than affecting gaze patterns within the alternative strategy. The latency data show that the biasing of targets to the lower right of the display, though encouraging overt gaze to proceed toward that location, does not specifically reinforce the strategy (Strategy 2) that dominates in the ULB condition. Consequently, the parallel search strategy (Strategy 1) described by Durgin (2003) is probably still employed predominantly in the LRB case. The identity of a distracting color (Set) is important to Strategy 1 because the distracting color interferes with the activation of the sensory search representation, and is

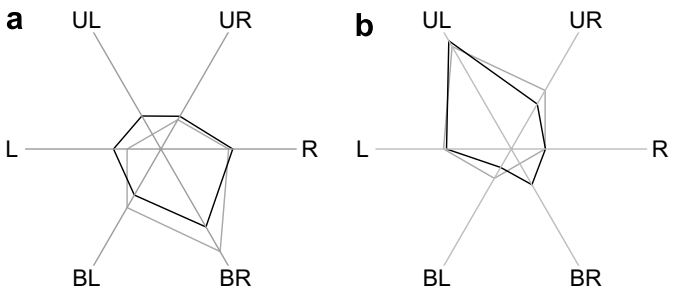


Fig. 7. Relative frequency of gaze errors to each of the six response locations in Experiment 3. Left panel shows data (black) for those in the LRB condition; right panel shows data for those in the ULB condition. The relative frequencies of targets appearing in the six locations is indicated by the gray lines.

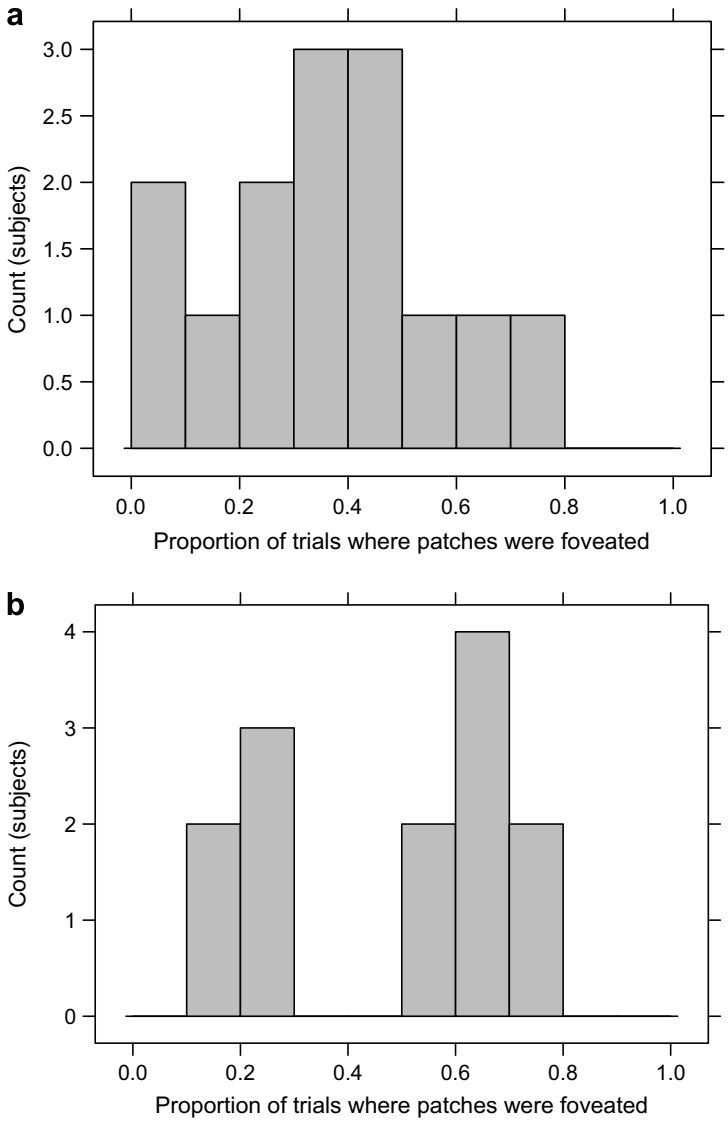


Fig. 8. Histograms of proportion of trials in Experiment 3 in which a response patch was foveated. Panel A represents subjects in the ULB condition; Panel B represents those in the LRB condition.

more interfering if the distracting color is a competing (established) search target.

6.4.1. Gaze bias shift

Although our participants' error gaze distributions tended to match the target location probabilities (Fig. 7), an alternative interpretation to statistical learning (Geng & Behrmann, 2002) is local sequential dependency effects (Walthew & Gilchrist, 2006). That is, error gazes that consisted of returns to recent targets could exactly match target probabilities without there being any long-term storage of target position probabilities. If the overall error gazes of the present experiment were matched in probability to the target location probabilities, but unrelated to the location of the target on the previous trial, the proportion of error gaze to the same location as the previous trial should be 22.5%. Local sequential effects would be indicated if matched-location error trials were more common than this. In fact, the average empirical proportions of gaze errors that matched the previous target location were 22.6% in the ULB condition and 22.8% in the LRB condition. The overall proportions (combining all 765 gaze error trials across subjects) were 22.0% and 22.8%, respectively. These values suggest that the probability matching that is evident in the gaze error trials was not simply due to the location of the target on the just-previous trial.

However, the sequential effects of Walthew and Gilchrist (2006) were based on previous movements of gaze. Because our participants did not move their gaze on most trials, we considered whether gaze error locations corresponded to the gaze location of the most recent trial in which gaze had shifted (if gaze was accurate). Here we found that prior gaze locations more strongly predicted gaze error locations (31.8%) in the ULB condition than did the previous target position, $t(12) = 3.54$, $p = 0.0041$. The average proportion (24.9%) did not differ reliably for

those in the LRB condition, $t(13) = 0.45$, $p > 0.10$. It therefore seems possible (though not proven) that sequential effects from actual movements of gaze may play a role in this task and that the role is greater for those participants for whom the latency data suggest the serial gaze strategy was more dominating (i.e., those in the ULB condition).

7. General discussion

In Experiment 1 we found that when the movement of gaze was treated as the response, there were large numbers of errors made, but that analysis of correct response latencies showed no effects of Match (having a color among the choices on the screen that matched the irrelevant text color). In Experiment 2 we monitored gaze and found that the distribution of first gaze "errors" was quite similar to that in Experiment 1. However, because these gaze errors did not count as responses, correct pointing responses were collected on most of these trials, with the result that the more typical results of both Match and Set were found in the latency data. Because we found an upper-left gaze bias in both Experiments 1 and 2, we manipulated the efficacy of this bias, in Experiment 3, by placing correct targets predominantly toward the upper left or predominantly toward the lower right. For those participants for whom the upper-left gaze bias was reinforced, response latency data showed larger than normal effects of Match and no effects of Set, suggesting that a cognitive matching strategy had been reinforced. For those participants for whom the upper-left bias was opposed, however, the relative components of Set and Match were similar to those in previous experiments (Durgin, 2003; Experiment 2 of this paper).

Taken together, these results suggest that the upper-left gaze bias found in Experiments 1 and 2 is part of a cognitive strategy – most likely a serial comparison strategy. (Strategy 2). When this strategy is thwarted by making gaze count as a response (Experiment 1), a distinct pattern of response latencies emerges in which only Set effects, not Match effects, are present. When Strategy 2 is reinforced (ULB condition of Experiment 3) a quite different pattern of response latencies emerges in which only Match effects are present. When the upper-left component of Strategy 2 is simply made ineffective (LRB condition of Experiment 3), performance resembles normal performance at the task and is dominated by latency patterns corresponding to parallel search effects (Set effects) indicative of Strategy 1 (parallel search following translation to a sensory code).

It is worth emphasizing that sensitivity to environmental structure (biasing of target location) seems to produce primarily a shift in cognitive strategy choice, and only secondarily a resetting of gaze parameters for the serial search strategy. This suggests that strategy components (e.g., gaze biases) are less easily modified by task feedback than is the choice of cognitive strategy. But the choice of cognitive strategy seems to be more easily modified by appropriate feedback, such as that provided in Experiment 3, where one strategy or the other was more successful. The feedback regarding the serial strategy in Experiment 1 was strictly negative.

We are not suggesting that the serial strategy is actually implemented entirely by overt movements of gaze, as most evidence contradicts this possibility (but see Findlay & Gilchrist, 1998). Moreover, exploratory gaze movements may be a serial component of a series of parallel searches (Zelinsky et al., 1997). Nonetheless the upper-left gaze bias found here seems to result from a kind of default, exploratory routine. Movements of gaze are, by definition, serial. Although it is possible that the upper-left gaze routine is based on adapting to a visual system for which the upper left is the region with noisiest information (see Efron & Yund, 1996), our latency and error data suggest that the lower left region is also poorly sampled. We do not think the bias is strictly related to linguistic materials (based on reading left to right) because we have found evidence of this same bias with searches for matches to visual textures (Lashinsky & Durgin, unpublished data). Nonetheless, the possible relation to cultural patterns of reading a page from the upper left cannot be ignored. It remains possible that one goal of refixation is to terminate processing of distracting information (see also Previc, Declerck, & de Brabander, 2005) or avoid searching at the center of the display. However, we have found evidence that the phenomenon is more general than this.

By analyzing gaze data from an earlier experiment (Durgin, 1999), we have found that there is evidence of a similar bias in a nearly information-less search task without a central target. In that experiment, a rectangular visual display with hundreds of oriented colored bars was used as a search display. The actual target of search (red crossed lines) was never present initially because there was a contingency that produced the target during the trial (see Durgin, 1999, for details). Thus, the initial gaze patterns in that task were essentially information-less. Fixation always started at the center of the display. By binning the initial movement of gaze according to its radial direction, the histogram of first gaze orientation shown in Fig. 9 was produced representing 3000 trials pooled from 20 subjects. There is clearly an upper-left bias for first gaze in that paradigm as well. This suggests that the upper-left bias is not task specific, but may represent a kind of general default strategy. We would argue that because choice itself is costly (e.g., Schwartz, 2004), having a default scanning initiation point may be useful because of the reduction in processing overhead (see also Araujo et al., 2001).

7.1. Implications for theories of reverse Stroop interference

Durgin (2003) argued that the reverse Stroop paradigm required a visual search based on a sensory representation of the target color and that Set effects were due to competition among sensory representations that were already potentiated. He showed that the type of response given (pointing to the correct patch or merely indicating if the correct patch was present) could vary without altering

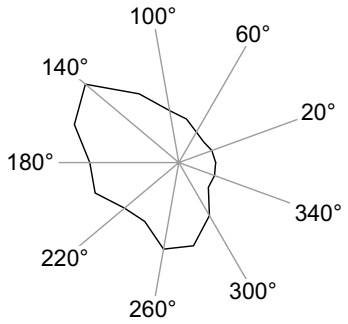


Fig. 9. Relative frequency of first gaze orientation (from central fixation) in an "information-less" visual search task (see Durgin, 1999, for details of method). Data are based on 3000 trials (150 trials, each, of 20 participants) and binned into 18 equiangular intervals. The display was rectangular, with an upper-left corner that would have corresponded to an angle 37° above the left horizontal. The most frequent orientation plotted here is 40° above the left horizontal.

the pattern of latency results and argued that this was because the search, itself, was the same. The data we have presented here does not contradict this idea, but it suggests that participants may sometimes respond based on a different search strategy. This alternative strategy involves no coding interference (and, hence, no Set effects) perhaps because the initial (verbal) code of the target word is retained. As a result, the task becomes a serial search that may involve translating a series of color patches into words. It must be emphasized that this hypothesis is not proven, though it is roughly consistent with the present data. It is possible that this second "strategy" reflects simply a heavier influence of uncontrolled exploratory scanning – a kind of failure of executive control.

Many theories of Stroop interference are basically associative, emphasizing the stronger connection-strengths between certain kinds of inputs and outputs (e.g., Cohen et al., 1990). Even some theories that proclaim themselves to be cognitive (e.g., Kornblum et al., 1990) seem to limit discussion to the relationship between stimulus and response without considering internal representations. Treisman and Fearnley (1969) used a matching task in which Stroop words might be set next to rectangles of color on a card. If the task was to say whether the color named by the word matched the color of the rectangle, they found interference from cases where the sensory colors matched when the word did not or when the sensory colors did not match when the word did. Naturally, if the task was to compare the color of the text to the colored rectangle, the word had no effect. Treisman and Fearnley argued persuasively that reversing the Stroop effect required only that "color itself be the response". This idea has been extended by Hommel (2004) more recently with his color-production training task.

As if to emphasize a continued role of response competition, Egeth et al. (1969) created a variant of the Treisman and Fearnley (1969) paradigm. They showed that if the words printed on the card in a matching task were "SAME" or "DIFF", instead of color words, then these words still had an interfering effect on saying whether the sensory colors were the same or different. This finding can help to explain the Match effect in the present experiment – and to explain why the Match effect might be most pronounced when the serial match-detection strategy is used. In a serial search looking for a match, the interference produced by a matching distracter color could arise because of a need to reject false kinds of match (i.e., of a color patch to the sensory color of the word) that arise along the way. This implies that the decision rules for responding are defined differently for this strategy than for the more typical (presumably parallel) search strategy that produces Set effects.

We have found evidence for at least two search strategies co-existing in the reverse Stroop paradigm, though our results emphasize that cognitive strategies are dynamic and adaptive. Human cognitive systems are very flexible, but the Stroop effect has fascinated many researchers by seeming to indicate surprising limits on cognitive flexibility. In the study of cognition, the easiest strategies to detect experimentally are those that fail to adapt fully and thereby reveal themselves in non-optimal patterns of behavior. The very intransigence of a strategy or bias, however, suggests that it may be highly adaptive in more normal circumstances. Although translation theories cannot account for all aspects of Stroop interference, they emphasize the idea that different forms of internal representation may involve different control structures, optimized for different kinds of tasks and strategies.

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Appendix. Details of saccade coding

The Eyelink includes software that provides real time analysis of gaze events. These events (in addition to instantaneous position estimates) can be communicated with the experimental computer in real time by an Ethernet link. In the experiments reported here, saccades detected by the Eyelink software were used to define relocations of the eye. Saccade initiation in such a system is detected by high accelerations of eye position (sampled at 250 Hz) and blinks are excluded by looking at concomitant changes in pupil size associated with blinks; saccades are discriminated from jitter by using a velocity profile trigger. The spatial calibration of such a system is only as accurate as the gaze of the observers during the calibration and drift correction procedures. For these experiments, the Eyelink's standard 9-point calibration display (corners, center, and

edges of screen) was used both to establish calibration and to validate that calibration. This method of calibrating the entire screen is ostensibly accurate to well within a degree, though variation in viewer fixation adds noise.

Because slight movements of the tracker with respect to the head (slippage) is possible during an experiment, each trial is preceded by a "drift correction" event: The subject gazed at the fixation mark and pressed a key to go on. Slight apparent departures from central gaze triggered slight corrections to the central calibration. Larger departures triggered a redo (to avoid corrections for cases where the subject failed to fixate on the correct location). During the experiments, a 9-point recalibration was undertaken at any time when drift correction failed repeatedly. Because of the constant drift correction, the calibration of the tracker is really only as good as the most recent drift correction event and some position noise is to be expected. About 5–10% of subjects recruited to participate could not be calibrated and were not run in the experiments.

Could the biases in gaze direction reported in this paper be an artifact of noisy and biased signals from the tracker? Although the altered bias in gaze errors in the BR condition of Experiment 3 argues against this possibility, we think it best to provide some graphical sense of how the movements of gaze were distributed spatially during the experiment. In Experiment 2, where gaze was free to move (the movement of the mouse represented the response) we stored all saccade events up to the termination of the trial. The statistical analyses in the paper are of the first saccade event that entered one of the target locations. Although a more stringent spatial criteria might have been used (e.g., within two degrees of the center of a target circle), it is equally reasonable that a less stringent criterion (proximity to a target circle) might have been used. In Fig. A1 are shown the end points of the first saccade detected by the Eyelink during each trial for the nine observers in Experiment 2 who most frequently fixated a target circle. Blue dots (if in color; otherwise gray dots) represent fixations on the correct target color. Red dots (if in color; otherwise black dots) indicate fixations on the wrong target color. Black dots (if in color; otherwise light gray) are those that ended in a non-target region. Trials on which no saccades

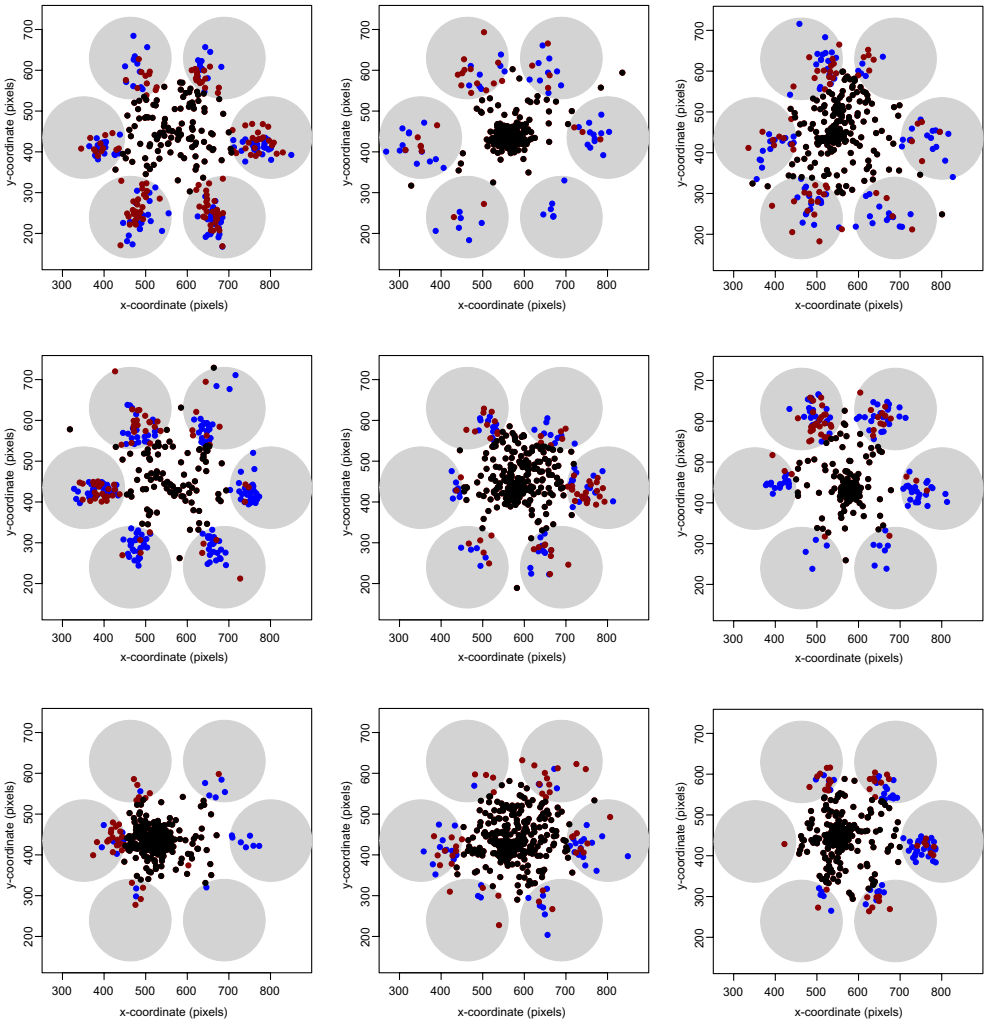


Fig. A1. Fixation data based on the first saccade for each of the nine subjects in Experiment 2 whose gaze most frequently landed on a target location. Dark (red if color image) dots indicate endpoints to the wrong color target.

were detected are not represented. Many of the central dots are clearly refixations within or near the central word, but a sizeable proportion appear to be consistent with radial movements of gaze toward one of the target regions. Fig. A1 illustrates both the noisiness of the eye data and its general fit to the display. Subjects shown in panels C, G, and I all show a noticeable leftward bias in their central refixations, consistent with attending to the initial portion of the longer target words (recall that the set of words used varied from subject to subject – for six-letter words it is likely that the second letter was often foveated), but each also shows a subset of refixations that are clearly radially divergent from the central word. Refixations that fall between regions of interest have been reported by Zelinsky et al. (1997) in the studies of naturalistic search patterns, so the variability in refixation locations evident in some of the data may reflect the fact that people do fixate on centers of mass between and among locations.

As further confirmation of this view, Fig. A2 shows the endpoint of the second saccade detected by the Eyelink on each trial for the same nine participants (considering only those trials where the first saccade did not fall on a target patch and where a second saccade was detected). It is now evident, for example, that the participant in Panel C is indeed distributing gaze (unevenly) among the six target locations. Although not presented here, the third saccade data for the participant shown in Panel H form a hollow ring suggesting that by the third saccade, the word was no longer a target for refixation. We regard this graphical data as a justification of the operational use of saccade endpoints detected by the Eyelink as a measure of saccadic endpoints that were or were not directed toward specific target locations. The use of the target circle as an outer-bound, though necessarily imperfect, seems a reasonable operationalization of target-directed gaze, based on the distribution of gaze data. Additional views of the gaze data may be viewed at http://www.swarthmore.edu/SocSci/fdurgin1/gaze07/.

In Fig. A3, similar data are plotted for Experiment 3 with first saccade endpoints represented in the upper six

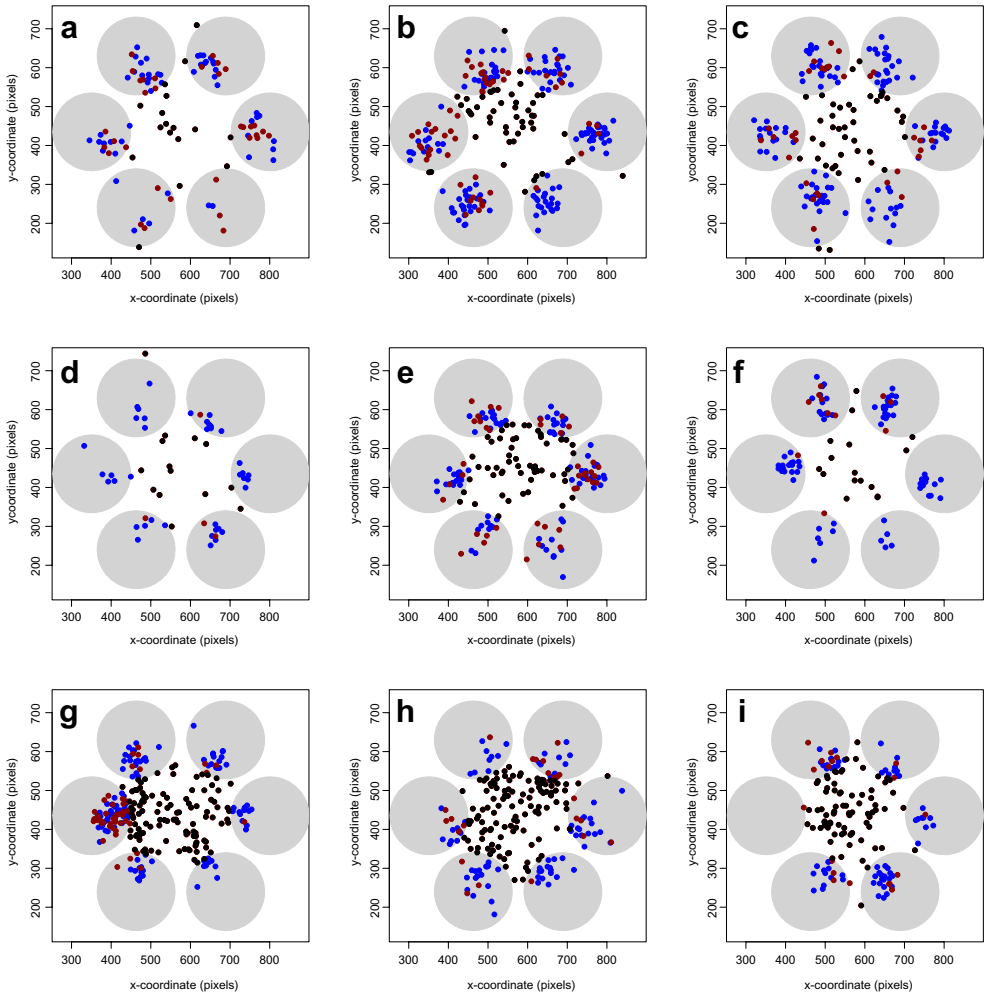


Fig. A2. Fixation data based on the second saccade for each of the nine subjects in Experiment 2 whose gaze most frequently landed on a target location. Dark (red if color image) dots indicate endpoints to the wrong color target. Only saccadic endpoints from locations not on targets (see Fig. A1) are shown. (Main analyses in the paper are based on the first target location to which a saccade reached on each trial.).

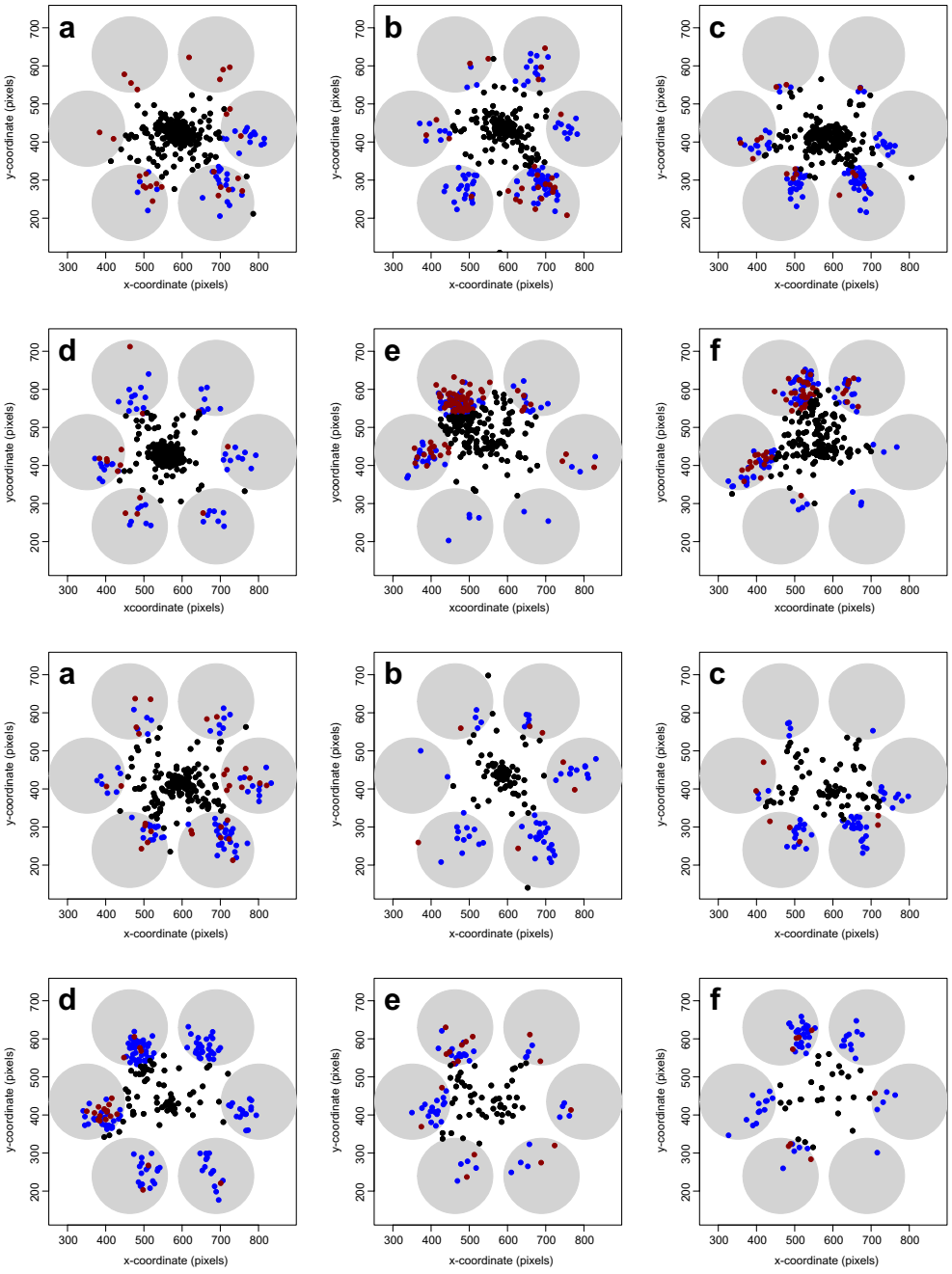


Fig. A3. Fixation data from Experiment 3 showing the first (top six panels) and second (bottom six panels) saccadic endpoints for six subjects chosen for making the most saccades to targets in each of the two conditions. A, B and C represent observers in the lower-right bias condition, while D, E and F represent observers in the upper-left bias condition.

panels and second saccade endpoints in the lower six panels. The data are from the three participants in each bias condition who had the highest frequency of gaze movement toward targets. As expected, the patterns of initial saccades are quite different depending on the bias of the target locations. It is evident that the subjects whose data are shown in panels A–C were in the lower-right bias condition, whereas those in D–F were in the upper-left bias condition.

Finally, in Fig. A4, we show one upper-left scan path from Experiment 1 (A) superimposed on the original displays (where refixation to a target was treated as a response regardless of fixation duration and terminated the trial) and three scan paths from Experiment 2 (B–D) illustrating upper-left saccades followed by refixations to other regions (sometimes near, rather than on target patches). Fixation durations are shown. In some cases (e.g., Panel D) fixations to the upper left were so brief that it is clear that the second saccade was being programmed before the first was even initiated. These scan paths are consistent with the idea that serial fixations often reflect partial information (Rao et al., 1996, 2002; Zelinsky et al., 1997).

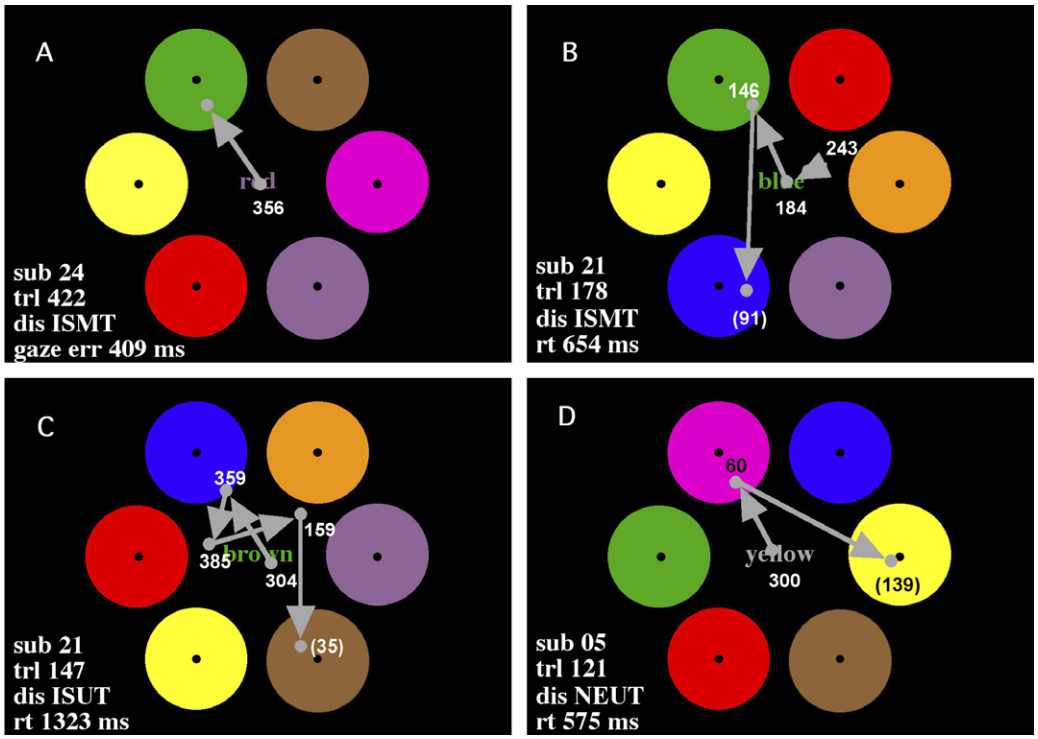


Fig. A4. Sample eye scan patterns for trials with first gaze to the upper left. Panel A is an error trial from Experiment 1, where gaze is the response. Panels B, C and D all represent trials from Experiment 2 where the ultimate (mouse-cursor) response was correct, though initial gaze was to the upper left. Small numbers represent fixation times (ms). Numbers in parentheses represent approximate time between final fixation and the (accurate) mouse response to the fixated target. The brevity of these times suggests that mouse movements were being planned before direct gaze reached the target.

References

Araujo, C., Kowler, E., & Pavel, M. (2001). Eye movements during visual search: The costs of choosing the optimal path. *Vision Research, 41*, 3613–3625.

Belky, E. J., & Motter, B. C. (1998). The guidance of eye movements during active visual search. *Vision Research, 38*, 1805–1818.

Christie, J., & Klein, R. (1995). Familiarity and attention: Does what we know affect what we notice? *Memory & Cognition, 23*, 547–550.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review, 97*, 332–361.

Dark, V. J., Vochatzer, K. G., & VanVoorhis, B. A. (1996). Semantic and spatial components of selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 22*, 63–81.

De Graef, P. (1998). Prefixational object perception in scenes: Objects popping out of schemas. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 315–338). Oxford: Elsevier.

De Houwer, J. (2003). On the role of stimulus–response and stimulus–stimulus compatibility in the Stroop effect. *Memory & Cognition, 31*, 353–359.

Deubel, H., & Schneider, W. X. (1996). Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Research, 36*, 1827–1837.

Durgin, F. H. (1999). Supporting the "Grand Illusion" of direct perception: Implicit learning in eye-movement control. In S. R Hameroff, A. W. Kaszniak, & D. J. Chalmers (Eds.), *Toward a science of consciousness III* (pp. 179–188). Cambridge: MIT Press.

Durgin, F. H. (2000). The reverse Stroop effect. *Psychonomic Bulletin & Review, 7*, 121–125.

Durgin, F. H. (2003). Translation and competition among internal representations in a reverse Stroop effect. *Perception & Psychophysics, 65*, 367–378.

Dyer, F. N. (1973). The Stroop phenomenon and its use in the study of perceptual, cognitive, and response processes. *Memory & Cognition, 1*, 106–120.

Efron, R., & Yund, E. W. (1996). Spatial nonuniformities in visual search. *Brain and Cognition, 31*, 331–368.

Egeth, H. E., Blecker, D. L., & Kamlet, A. S. (1969). Verbal interference in a perceptual comparison task. *Perception & Psychophysics, 6*, 355–356.

Findlay, J. M. (1980). The visual stimulus for saccadic eye movements in human observers. *Perception, 9*, 7–21.

Findlay, J. M. (1997). Saccade target selection in visual search. *Vision Research, 37*, 617–631.

Findlay, J. M., Brown, V., & Gilchrist, I. D. (2001). Saccade target selection in visual search: The effect of information from the previous fixation. *Vision Research, 41*, 87–95.

Findlay, J. M., & Gilchrist, I. D. (1998). Eye guidance and visual search. In G. Underwood (Ed.), *Eye guidance in reading and scene perception* (pp. 295–312). Oxford: Elsevier.

Geng, J. J., & Behrmann, M. (2002). Probability cueing of target location facilitates visual search implicitly in normal participants and patients with hemispatial neglect. *Psychological Science, 13*, 252–520.

Gersch, T. M., Kowler, E., & Dosher, B. (2004). Dynamic allocation of visual attention during the execution of sequences of saccades. *Vision Research, 44*, 1469–1483.

Glaser, W. R., & Glaser, M. O. (1989). Context effect in Stroop-like word and picture processing. *Journal of Experimental Psychology: General, 118*, 13–42.

Hommel, B. (2004). Coloring an action: Intending to produce color events eliminates the Stroop effect. *Psychological Research, 68*, 74–90.

Irwin, D. E. (2004). Fixation location and fixation duration as indices of cognitive processing. In F. Ferreira & J. M. Henderson (Eds.), *The interface of language, vision, and action: Eye movements and the visual world* (pp. 105–133). New York: Psychology Press.

Klein, G. S. (1964). Semantic power measured through the interference of words with color-naming. *American Journal of Psychology, 77*, 576–588.

Kornblum, S., Hasbroucq, T., & Osman, A. (1990). Dimensional overlap: Cognitive basis for stimulus–response compatibility – a model and taxonomy. *Psychological Review, 97*, 253–270.

Kowler, E., Anderson, E., Dosher, B., & Blaser, E. (1995). The role of attention in the programming of saccades. *Vision Research, 35*, 1897–1916.

Kustov, A. A., & Robinson, D. L. (1996). Shared neural control of attentional shifts and eye movements. *Nature, 384*, 75–77.

Lemon, J., Bolker, B., Oom, S., Klein, E., Rowlingson, B., Wickham, H., et al. (2007). Plotrix: Various plotting functions. R package version 2.2-3.

Levy-Schoen, A. (1969). Détermination et latence de la réponse oculuomotrice à deux stimulus simultanés ou successifs selon leur excentricité relative [Determination and latency of the oculomotor response to two simultaneous or successive stimuli according to their relative eccentricity]. *L'Année Psychologique, 69*, 373–392.

Levy-Schoen, A. (1974). Le champ d'activité du regard: Données expérimentales [The movement of gaze: Experimental data]. *L'Année Psychologique, 74*, 43–66.

MacLeod, C. M. (1991). Half a century of research on the Stroop effect: An integrative review. *Psychological Review, 109*, 163–203.

McConkie, G. W., & Rayner, K. (1975). The span of the effective stimulus during a fixation in reading. *Perception & Psychophysics, 17*, 578–586.

McConkie, G. W., & Zola, D. (1987). Visual attention during eye fixations while reading. In M. Coltheart (Ed.), *Attention and performance XII: The psychology of reading* (pp. 385–401). Hillsdale, NJ: Lawrence Erlbaum.

Melara, R. D., & Mounts, J. R. (1993). Selective attention to Stroop dimensions: Effects of baseline discriminability, response mode, and practice. *Memory & Cognition, 21*, 627–645.

Motter, B. C., & Belky, E. J. (1998). The zone of focal attention during active visual search. *Vision Research, 38*, 1007–1022.

Peterson, M. S., Kramer, A. F., & Irwin, D. E. (2004). Covert shifts of attention precede involuntary eye movements. *Perception & Psychophysics, 66*, 398–405.

Previc, F. H., Declerck, C., & de Brabander, B. (2005). Why your "head is in the clouds" during thinking: The relationship between cognition and upper space. *Acta Psychologica, 118*, 7–24.

Proctor, R. W. (1978). Sources of color-word interference in the Stroop color-naming task. *Perception & Psychophysics, 23*, 413–419.

Rao, R. P. N., Zelinsky, G. J., Hayhoe, M. M., & Ballard, D. H. (1996). Modeling saccadic targeting in visual search. In M. Mozer, D. Touretzky, & M. Hasselmo (Eds.). *Advances in neural information processing systems* (Vol. 8). Cambridge, MA: MIT Press.

Rao, R. P., Zelinsky, G. J., Hayhoe, M. M., & Ballard, D. H. (2002). Eye movements in iconic visual search. *Vision Research, 42*, 1447–1463.

R Development Core Team (2007). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Schwartz, B. (2004). *The paradox of choice*. New York: Harper Collings.

Stelmach, L. B., Campsall, J. M., & Herdman, C. M. (1997). Attentional and ocular movements. *Journal of Experimental Psychology: Human Perception and Performance, 23*, 823–844.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643–661.

Sugg, M. J., & McDonald, J. E. (1994). Time course of inhibition in color-response and word-response versions of the Stroop task. *Journal of Experimental Psychology: Human Perception and Performance, 20*, 647–675.

Treisman, A. M., & Fearnley, S. (1969). The Stroop test: Selective attention to colours and words. *Nature, 222*, 437–439.

Virzi, R. A., & Egeth, H. E. (1985). Toward a translational model of Stroop interference. *Memory & Cognition, 13*, 304–319.

Walthew, C., & Gilchrist, I. D. (2006). Target location probability effects in visual search are an effect of sequential dependencies. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 1294–1301.

Zelinsky, G. J., Rao, R. P. N., Hayhoe, M. M., & Ballard, D. H. (1997). Eye movements reveal the spatiotemporal dynamics of visual search. *Psychological Science, 8*, 448–453.